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Thermal recovery of petroleum by electrical heating

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THERMAL RECOVERY OF PETROLEUM BY ELECTRICAL HEATING

BY

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A

THESIS

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Approved by C. M. Davis
Assistant Professor of Petroleum Engineering

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INTRODUCTION

Although this thesis is presented in partial fulfillment of the requirements for the degree of Master of Science in Chemical Engineering, the research problem is one in Petroleum Production Engineering. The investigation was conducted as a problem in Petroleum Engineering.

The recovery of petroleum in ordinary methods of field exploitation is estimated to be only 10 to 25 per cent of the original oil content of the reservoir rock. (1) The greater part of the oil originally

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(1) Uren, L. C., Petroleum Production Engineering, Exploitation, 2nd Ed. N. Y., McGraw-Hill, pp. 29-48, 1939.

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present in the reservoir rock is left unrecovered as a result of the forces of capillarity and adhesive retention of the oil on the mineral surfaces. Also, a large part of the oil is retained in the reservoir rock because the available expulsive energy is inadequate to overcome the resistance offered by the rock pores through which the oil must flow to reach the well outlets.

There are several natural forces which are operative in expelling oil from the reservoir rock. These forces are: (1) the expanding force of high pressure natural gas in the reservoir, (2) the buoyant force of encroaching edge water, and (3) the force of gravity. The expanding gas may be either free gas which is present in the form of a primary gas cap, or gas in solution which is released upon reduction of the reservoir pressure. The fluid pressures created by operation of these forces cause the reservoir fluids to move from areas of high pressure in the formation to those of lower pressure in the vicinity of the recovery wells.

This movement is opposed by certain retentive forces inherent in the reservoir. These forces are capillarity, adhesion, and pore friction. Energy furnished by application of the expulsive forces is consumed in overcoming these retentive forces, and the extent to which oil is recovered depends upon the relative magnitude of the expulsive and retentive forces and the extent to which the expulsive forces are controlled and utilized.

The use of secondary recovery methods make it possible to recover some of this remaining oil, but even with the most efficient secondary recovery methods, it is estimated that only 50 to 60 per cent of the oil originally present in the reservoir is recoverable. [2]

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(2) Uren, Op. cit., pp. 414-459.

Secondary recovery methods involve application of artificially developed forces or energy not naturally brought to bear in production by commonly used methods of flowing and pumping. These methods include application of vacuum to wells, gas or air injection methods, and methods involving flooding of the reservoir rock with water or aqueous solutions containing water-soluble flooding agents.

Since 40 per cent or more of the oil contained in a reservoir is usually left after primary and secondary methods of recovery have been applied, it has been a matter of considerable interest to devise methods whereby a portion of this remaining oil could be produced.

The use of thermal energy should provide a means of expelling the fluids from the reservoir. If enough energy could be injected into the reservoir in the form of heat, it should provide sufficient expulsive force to drive a portion of the fluids from the reservoir.

Taliaferro and Stanfield [3] state that laboratory determinations

(3) Taliaferro, D. B., and Stanfield, K. E., Asphaltic Sands Occuring in Oil Fields, World Oil, Vol. 128, No. 13, pp. 82-86, 1949.

show reserves of many millions of barrels of oil locked up in asphaltic sands. This material is largely present as asphalt rather than as crude oil. For the field under consideration, no appreciable amount of oil has been recovered by water flooding. This material, which is classified as "asphaltic pyrobitumen", has been obtained by laboratory retorting, but is not recoverable by extraction methods.

It appears possible that a portion of this organic material could be recovered if sufficient heat could be added to the reservoir to cause this bitumen to flow.

The addition of heat to the oil reservoir would have the effect of lowering the viscosity of the oil. It would also have the effect of reducing the surface tension of the oil and the interfacial tension between oil and water in the reservoir. This would cause a reduction in capillary pressure and a consequent reduction in the resistance to oil flow.

Heat applied to the reservoir should free the locked gases, which would expand as a result of the increase in temperature. This should provide an expulsive force to drive the reservoir fluids from the formation. Thermal action should have the effect of liquifying the congealed hydrocarbons in the formation allowing them to be set in motion by expanding gas or by gravity.

It is the purpose of this investigation to study the feasibility of recovering oil from laboratory size cores by passing electric current through the formation. If a voltage of sufficient magnitude could be applied to the formation to cause a flow of current, the formation would be heated. This heat should stimulate the flow of oil. The expansion of any gas present in the core together with the formation of hydrocarbon vapors should provide sufficient expulsive force to drive oil from the core.

The effect of power expenditure, the necessary voltages, the changes of conductivity and power factor of the formation, temperatures, and heating rates were investigated and will be presented in the body of the thesis.

REVIEW OF LITERATURE

A search of the literature was made and no information could be found concerning the recovery of petroleum by electrical heating.

Gibbon (4) reports a method of oil recovery in which a heat exchanger was used to heat the oil formation. The heat exchanger was placed in a well and superheated air used as the heating medium. This method is reported to increase the production of wells as far away as 1200 feet from the well in which the heat exchanger was installed.

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(4) Gibbon, A., Thermal Principle Applied to Secondary Oil Recovery, Oil Weekly, Vol. 115, No. 10, pp. 170-174, 1944.

DISCUSSION

The experimental approach decided upon was to determine the amount of oil obtainable by other laboratory methods and to compare these results with those obtained by electrical heating. In this manner the oil recovery obtained in the laboratory electrical apparatus could be estimated.

The oil content of the sand was determined by extraction and by retorting. The oil indicated by extraction corresponded to the actual oil present in the formation as liquid oil, and for the asphaltic sand, the oil content obtained by retorting corresponded to the liquid petroleum plus the organic material convertible to liquid oil by heating. The recovery obtained by electrical heating was compared with the retort analysis and with the extraction analysis.

Since the quantity of oil sand available at the start of the investigation was considered to be insufficient, it was decided to use this sample for preliminary investigations and to obtain another oil sand for complete study. The preliminary investigations were made to determine the magnitude of voltages that might be required to obtain suitable current flow.

The first oil sand, on which the preliminary investigations were made, was an asphaltic sandstone. The origin of this core was not known. The second sample was a Vernon County, Missouri, sandstone. This sample was taken from an oil property in the vicinity of Richards, Missouri, in which a shaft had been dug into the formation. The oil sand was part of the material which had been mined from the shaft. This sample had been exposed to the air for some time. The oil bearing formation in this vicinity varied from 100 to 300 feet in depth and had a thickness of about 30 feet. (5)

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(5) Wilson, M. E., The Occurence of Oil and Gas in Missouri, Missouri Bureau of Geology and Mines, Vol. XVI, 2nd series, pp. 118-124, 1922

RETORT ANALYSIS

The retort analysis was made using a Fischer retort as recommended by the U. S. Bureau of Mines for the analysis of oil shales. (6) The

(6) Stanfield, K. E., and Frost, I. C., Method of Assaying Oil Shale by a Modified Fischer Retort, U. S. Bureau of Mines, Report of Investigations, No. 4477, p. 13.

apparatus consisted of a cast aluminum retort fitted with a steel delivery tube through which the vapors could pass to a collecting flask set in a cold water bath. A gas collecting flask was added to recover any non-condensible vapors. The retort was heated with a gas burner. The total oil and water content was determined by weighing. The water content was found by measuring the volume of water collected. The oil content was taken as the difference between the total liquid and weight of water. A pulverized sample of the oil sand was used for the analysis.

The oil sand was heated at various rates and at various temperatures in an attempt to determine an optimum recovery. For the asphaltic core, the maximum recovery by retorting was taken as the total oil content, and for the Missouri sandstone, the recovery by extraction was taken as the total oil content. No gas was obtained by retorting.

The effect of retorting temperature on oil recovery for the asphaltic sand is shown in figure 4. Figure 5 shows the effect of retorting temperature on oil recovery for the Missouri sandstone. It was found that the maximum oil recovery for both oil sands was obtained at 500°C. This was the maximum temperature that could be obtained using the aluminum retort.

The time rate of oil recovery by retorting at 350°C is shown in figure 6.

TABLE 1

OIL RECOVERY FROM ASPHALTIC CORE BY RETORTING

Temperature, °C	Time of retort-ting, hours	Oil recovery, % of core	Oil recovery % of total oil content
250	4	0.20	7.9
300	4	0.49	19.3
350	3.5	0.76	29.9
400	3	1.53	60.3
450	3	2.30	90.7
500	2.5	2.54	100.0

TABLE 2

EFFECT OF HEATING RATE ON OIL RECOVERY BY RETORTING, ASPHALTIC CORE

Temperature, degrees C	Heating rate, temperature rise, degrees C/min.	Total heating time, hrs.	Oil recovery % of core
500	4	3	2.54
500	6	2.5	2.56
500	8	2	2.56
450	4	2.5	1.99
450	8	2.5	2.02

TABLE 3

EFFECT OF RETORTING TEMPERATURE ON OIL RECOVERY, MISSOURI SANDSTONE

Retorting temperature, °C	Oil recovery % of core by wt.	Oil recovery % of total oil content
300	1.025	18.32
350	2.205	39.4
400	4.27	76.3
450	5.12	91.6
500	5.12	91.6

TABLE 4

TIME RATE OF OIL RECOVERY BY RETORTING AT 350°C, MISSOURI SANDSTONE

Time, hours	Volume of oil recovered, cc.	Oil recovery % of total content
0	0	0
0.25	0.30	4.58
0.50	0.80	12.2
0.75	1.20	18.3
1.0	1.45	22.1
1.25	1.62	24.7
1.50	1.80	27.5
1.75	1.90	29.0
2.0	2.00	30.6
2.17	2.05	31.3
2.33	2.10	32.0
2.50	2.12	32.4
2.67	2.18	33.3
2.83	2.20	33.6
3.00	2.20	33.6
3.17	2.27	34.6
3.33	2.30	35.1

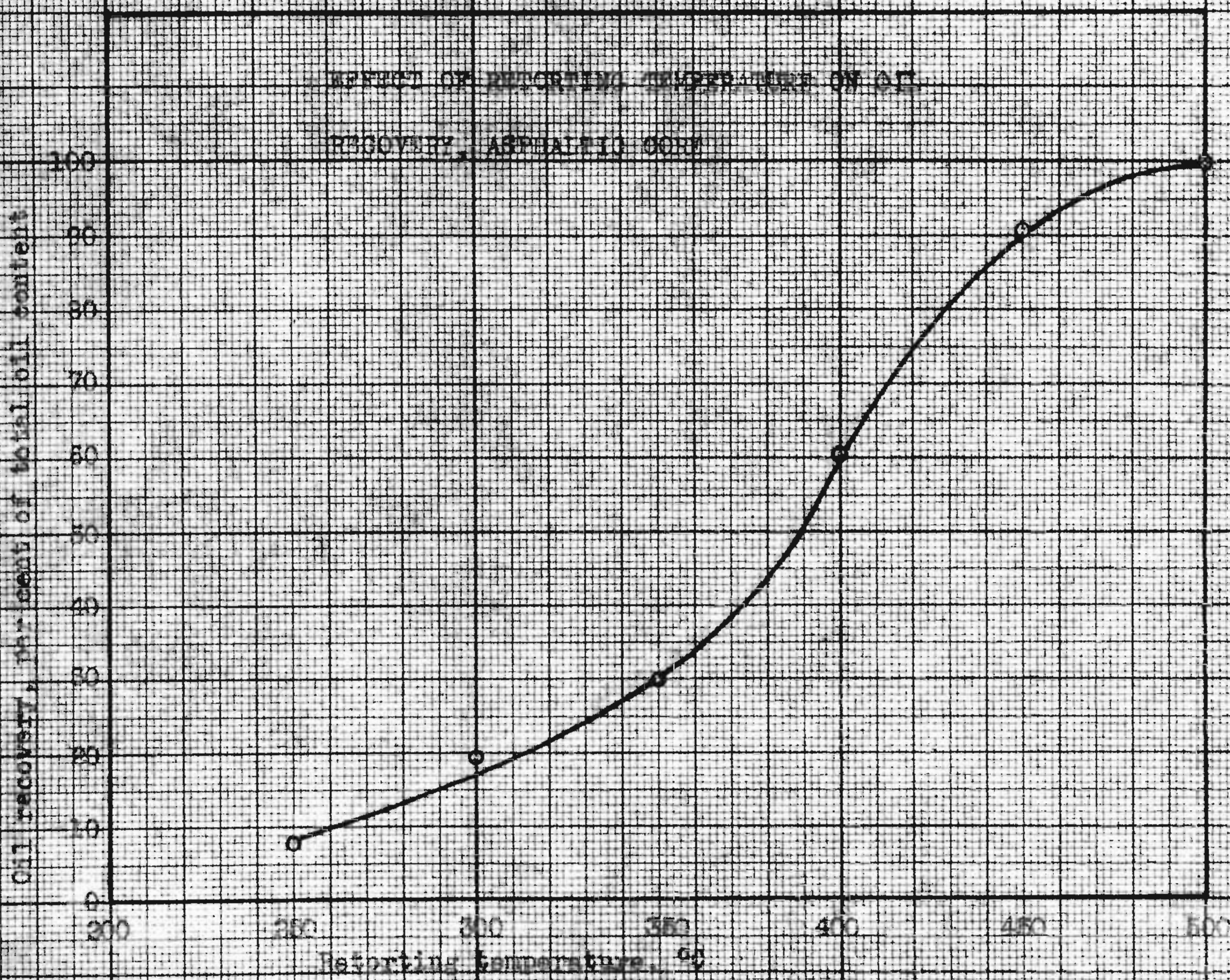

EFFECT OF RETORTING TEMPERATURE ON OIL
RECOVERY, ASPHALTIC CORE
Oil recovery, per cent of total oil content
100
90
80
70
60
50
40
30
20
10
0
200
250
300
350
400
450
500
Retorting temperature, °C

Figure 1

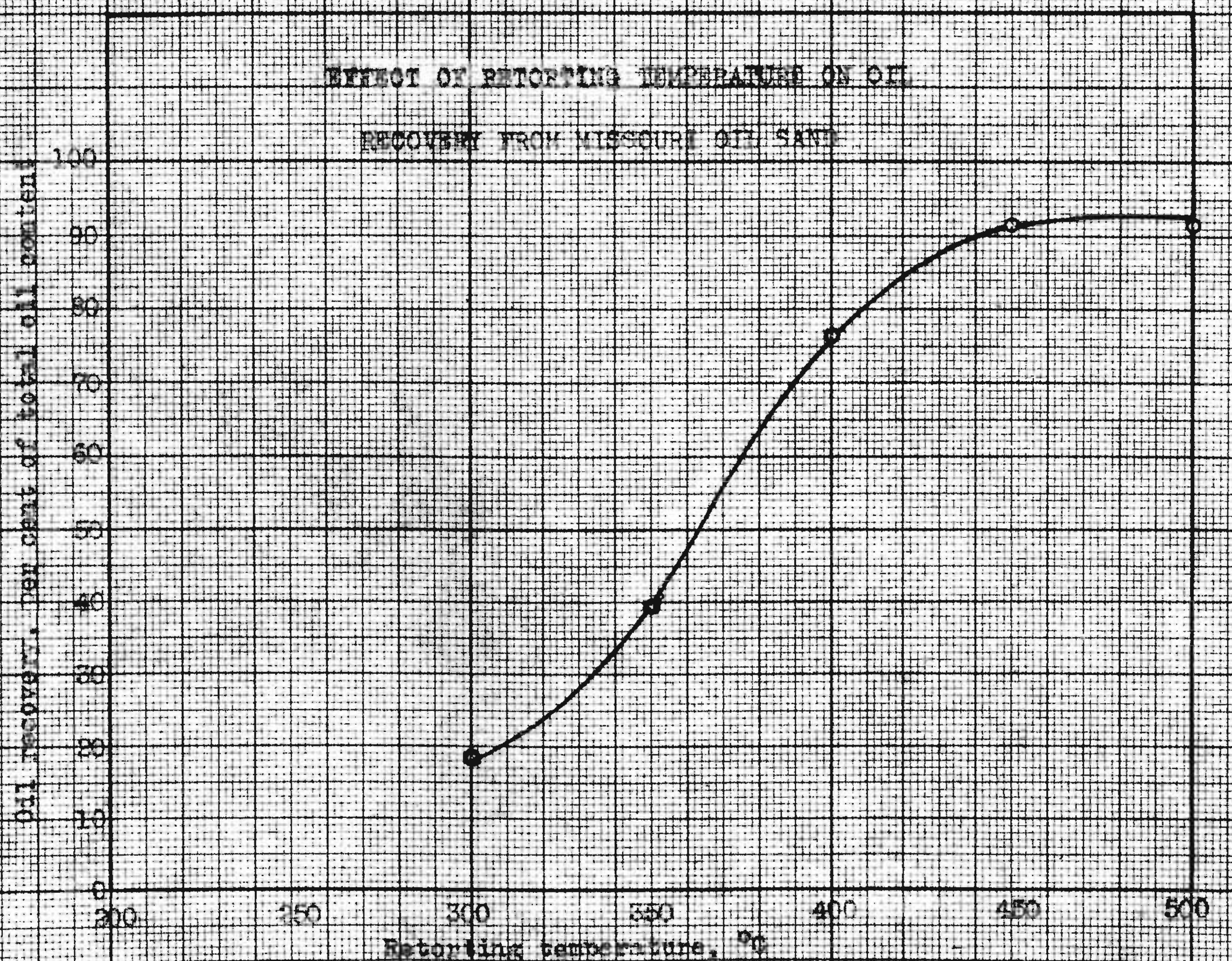

EFFECT OF RETORTING TEMPERATURE ON OIL
RECOVERY FROM MISSOURI OIL SAND
Oil recovery, per cent of total oil content
100
90
80
70
60
50
40
30
20
10
0
200
250
300
350
400
450
500
Retorting temperature, °C

Figure 12

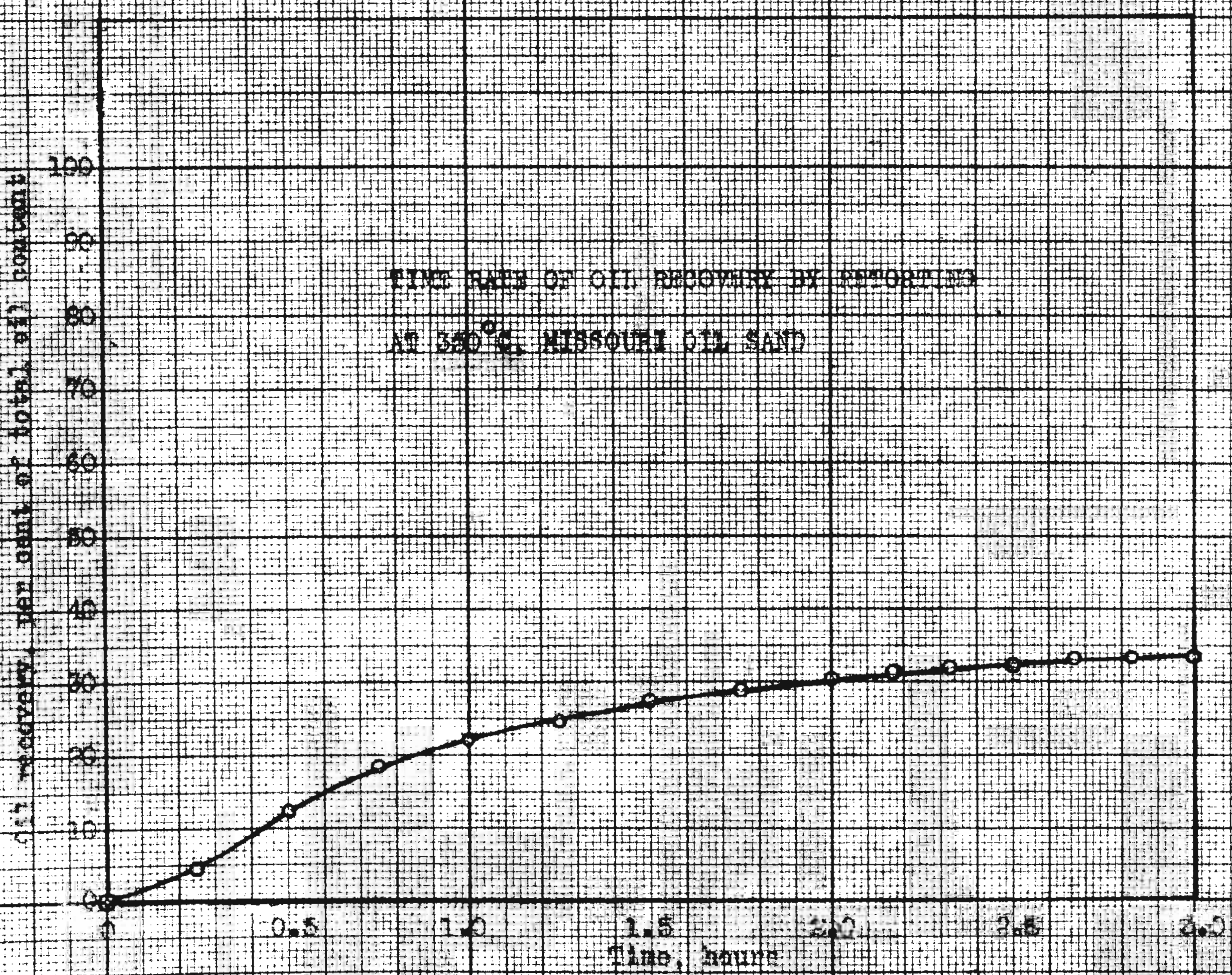

TIME RATE OF OIL RECOVERY BY RETORTING
AT 350°C, MISSOURI OIL SAND
Oil recovery, per cent of total oil content
100
90
80
70
60
50
40
30
20
10
0
0
0.5
1.0
1.5
2.0
2.5
3.0
Time, hours

Figure 3

FLUID CONTENT BY EXTRACTION

A portion of the oil sand was placed in a standard Soxhlet [7] ex-

(7) Uren, L. C., Petroleum Production Engineering, Development, 3rd Ed. N. Y., McGraw-Hill, pp. 672-675, 1948.

traction apparatus and the oil extracted from it. The extracting fluids used were benzene and carbon disulfide. The sample was dried in an oven and the oil content determined by the loss in weight of the sample.

For determining water content, the sample was extracted with toluene in the apparatus prescribed by the American Society for Testing Materials. [8] This apparatus consisted of a distilling flask connected

(8) Standard Test for Water in Petroleum Products and Other Bituminous Materials, A. S. T. M. Standards, Part IIIa, Test D-95-46, pp. 331-334, 1946.

through a water trap to a vertical reflux condenser. A sample of the sand was placed in the flask with toluene and the extraction carried out until the volume of water in the trap became constant. The volume of water was then determined and converted into weight of water by using a value of one for the specific gravity of water.

TABLE 5

FLUID CONTENT OF ASPHALTIC SAND

	Sample 1	Sample 2	Sample 3	Average
Water content, per cent by weight	0.72	0.22	0.23	0.39
Benzene soluble matter, per cent by weight	2.82	2.73	2.75	2.77
CS_2 soluble matter, per cent by weight	2.30	2.41	2.42	2.37
Oil content by retorting, per cent by weight	2.56	2.54	2.56	2.55

TABLE 6

FLUID CONTENT OF MISSOURI SANDSTONE

	Sample 1	Sample 2	Average
Water content, per cent by weight	0.19	0.25	0.22
Benzene soluble matter, per cent by weight	5.59	5.63	5.61
Oil content by retorting, per cent by weight	5.18	5.34	5.26

PROXIMATE ANALYSIS

The procedure was that used for the proximate analysis of coal except that no volatile matter was determined.

TABLE 7

PROXIMATE ANALYSIS OF ASPHALTIC SAND

Moisture, per cent by weight	0.56	0.62	0.65
Ignition loss (organic matter), per cent by weight	8.03	8.30	8.12
Ash (mineral matter), per cent by weight	91.41	91.08	91.23

TABLE 8

PROXIMATE ANALYSIS OF MISSOURI SANDSTONE

Moisture, per cent by weight	0.29	0.31
Ignition loss (organic matter), per cent by weight	8.47	8.48
Ash (mineral matter), per cent by weight	91.24	91.21

FLUID SATURATION

The porosity was measured using a porosimeter in which the bulk volume was measured by the displacement of mercury and the grain volume measured by the displacement of air. The water volume was that measured by extraction. The oil was obtained from the oil content determined by extraction and the density of the oil. The water saturation was the per cent of the total pore space occupied by the water, and the oil saturation was the per cent of pore space occupied by oil. The remaining pore space was termed the gas or air saturation. No determination of fluid saturation was made for the asphaltic core.

TABLE 9

FLUID SATURATION OF MISSOURI SANDSTONE

Porosity, per cent of total volume	21.90
Oil saturation, per cent of pore space	67.40
Water Saturation, per cent of pore space	2.03
Gas (air) saturation, per cent of pore space	30.57

DETERMINATION OF PERMEABILITY

The permeability of the sand cores were determined with a laboratory permeameter. The cores were sealed in a rubber core holder and placed in the permeameter. Nitrogen was forced through the core and the pressure drop across the core measured together with the rate of flow of the nitrogen. The permeability was computed by means of the Darcy equation:

$$K = \frac{Z\,Q\,L}{A(P_2 - P_1)}$$

Where K is the permeability in darcies, Z is the viscosity of the nitrogen in centipoises, Q is the rate of flow of nitrogen in cubic centimeters per second, L is the length of the core in centimeters, A is the cross section area of the core in square centimeters, and $P_2 - P_1$ is the pressure drop across the length of the core in atmospheres. Permeabilities were determined for cores in which the fluids had been removed by extraction.

The permeability of the asphaltic sand was found to be 15.3 millidarcies, and the permeability of the Missouri sandstone 58.9 millidarcies.

DETERMINATION OF RESISTIVITY

The resistivity of the formation was determined by measuring the resistance with an ohmmeter and calculating the resistivity from the resistance and dimensions of the core. Electrical contact with the core was made by means of pools of mercury at either end of the core. The resistivity of the asphaltic core was found to be 11,600,000 ohm-cm., and the resistivity of the Missouri sandstone 5,100,000 ohm-cm..

DENSITY OF OIL OBTAINED FROM RETORT ANALYSIS

The density of the oil obtained from the asphaltic core was found to be 0.876 grams/cubic centimeter, and the density of the oil from the Missouri sandstone found to be 0.855 grams/cubic centimeter. These densities were measured at 20°C. This corresponds to an A. P. I. gravity of 29° for the asphaltic core and 33.4° for the Missouri sandstone.

DETERMINATION OF BREAKDOWN POTENTIAL OF ASPHALTIC CORE

Since the resistivity of the asphaltic sand was very high, it appeared that current could be made to flow only by a breakdown of the resistance. If sufficiently high voltage could be impressed to cause an initial flow of current, it was thought that this would cause carbonization along the path of the current. This would increase the conductivity of the core, making it possible to heat the core by passage of current. To determine if this breakdown occurred and what voltage was required to accomplish it, the sample was placed between electrodes across the secondary of a 230/6900 volt transformer. The electrodes were steel discs placed against the ends of the cylindrical core. An ammeter and voltmeter were connected in the primary with a circuit breaker set for 25 amperes. The impressed voltage in the primary was controlled by means of a power stat.

It was found that when a high voltage was impressed across the core, the resistance broke down suddenly, causing a very high current to flow through the core. This current increased at such a rapid rate that it was impossible to determine its magnitude, but it was sufficiently high to throw the circuit breaker. This breakdown was accompanied by a splitting of the core. The cores were examined after being broken down, and it was found a small path of carbonization was present along the fracture of the core. The voltages required for three cores are listed in Table 10.

TABLE 10

BREAKDOWN VOLTAGES REQUIRED FOR ASPHALTIC CORE

Sample number	Length, in.	Diameter, in.	Breakdown voltage
1	1-1/8	15/16	6000
2	1-1/8	15/16	3000
3	1-5/32	15/16	1000

TABLE 11

CURRENT FLOW BEFORE BREAKDOWN, ASPHALTIC CORE

Sample number 1 (6000 volt breakdown)

Impressed Voltage	Primary Current Flow, amperes
750	0
1500	0
1800	0
2400	0.1
3000	0.3
3900	0.4
4800	0.5

Sample number 2 (3000 volt breakdown)

Impressed Voltage	Primary Current Flow, amperes
1500	0.1
1800	0.15
2400	0.50

Since the conductivity of the core changed rapidly after breakdown, it was thought that a constant current transformer might be suitable for controlling the input current to the core. The samples, after being broken down were placed between electrodes across the secondary of a constant current transformer. The current maintained by the constant current transformer, which was rated at 6.6 amperes, was found to be too great. Temperatures were reached which fused the core and melted the steel electrodes. It was found that the conductivity increased rapidly as heating progressed, and at the end of the run that only 280 volts were required for the flow of 6.5 amperes. Since only two cores were available, these tests were run only to determine in a general manner the feasibility of using a constant current transformer.

ELECTRICAL HEATING TESTS FOR MISSOURI SANDSTONE

The apparatus used for the electrical heating tests is shown in illustration 6. The core was held in the reaction tube between the electrodes. The reaction tube was connected by means of glass tubing to a gas collecting flask. A cooling coil was placed in the line to condense any oil vapors that might come from the reaction tube. The reaction tube was a length of one inch diameter transparent quartz tubing. The electrodes were one-fourth inch in diameter steel rods. Electrode contact was made by drilling holes one-fourth inch in diameter and one-fourth inch deep into either end of the core and pushing the electrodes into these holes. Oil was recovered in the bottom of the reaction tube and gas was collected in the gas collecting flask. The electrical hook-up is shown in illustration 7.

The sand cores were weighed and placed in the apparatus. Voltage was impressed across the sample, using an induction regulator to control the voltage. It was found that no current could be made to flow with the maximum voltage of the apparatus, which was 6000 volts.

Since the sand had a very low water content, it was thought that they had dried out considerably after being taken from the formation. It was decided to try to artificially saturate the cores with salt water and again try to obtain a flow of current in the apparatus. To do this the cores were first placed under vacuum to remove most of the air from the sample. The vacuum was applied using a water aspirator. The sample was then placed in a 5% salt water solution and a pressure of 200 pounds per square inch applied. The core was weighed before and after saturation. The final salt water content was calculated from the original water content and the gain in weight due to the salt water saturation.

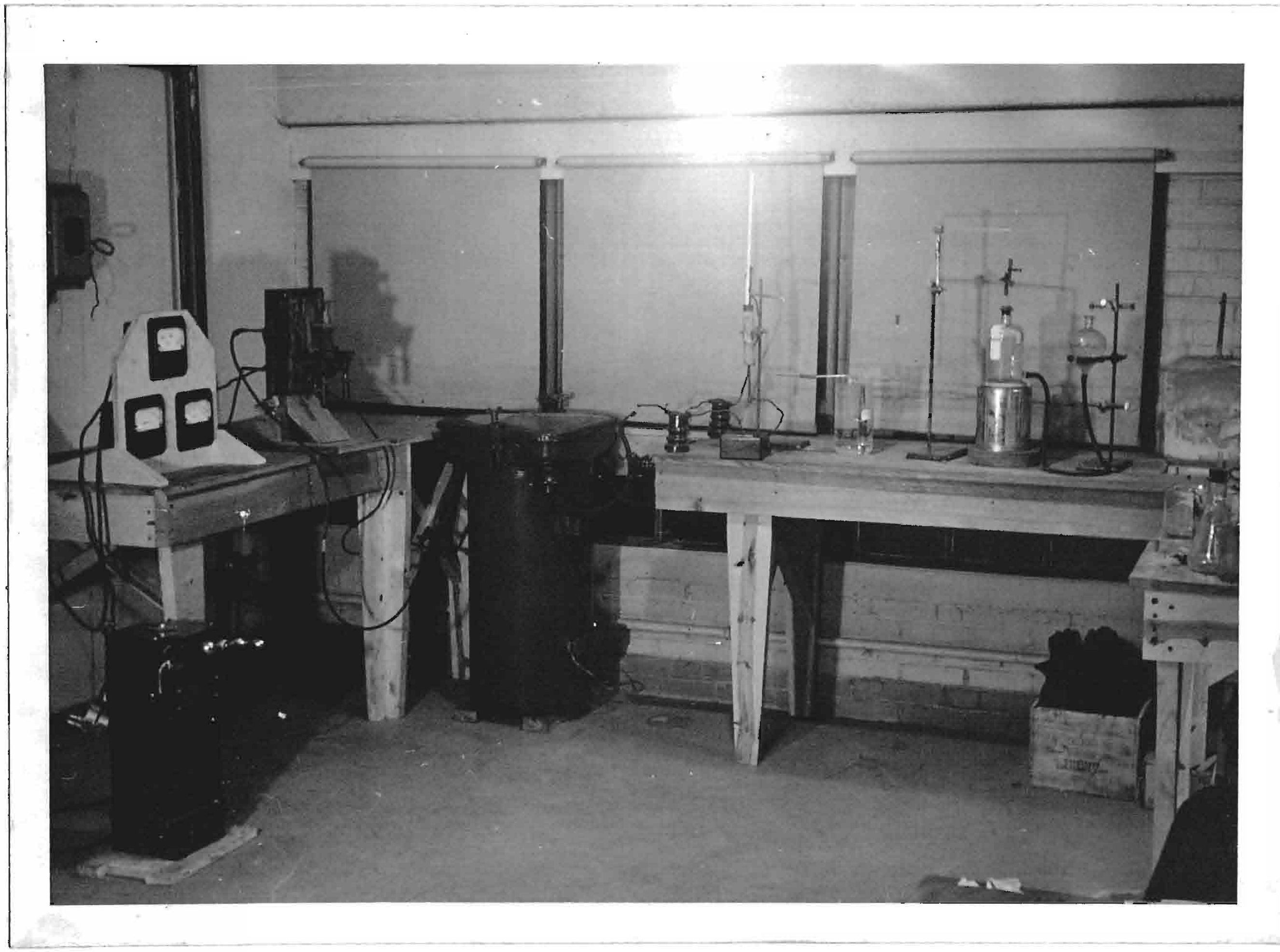
The core was again placed in the apparatus and it was found that current could be made to flow.

It was found that the current increased as the impressed voltage was increased for a short time, then the current dropped and no readable current was obtained. As the voltage was further increased a point was reached where the current surged to very high values almost instantaneously. This point was the "breakdown" point. From this point the resistance decreased rapidly upon further heating. It was found that it was impossible to obtain sufficient current flow in the secondary with the 1:30 transformer in the line, without excessive current in the primary. After breakdown the transformer was removed from the line and heating was continued with a 220 volt circuit. This was continued until no further increase in the gas volume in the collecting flask was noted. This occurred at about the same time that the resistance of the sample reached a minimum or became substantially constant.

In order to keep the heating effect substantially constant, each determination was conducted at constant power. A different power input was used for each determination.

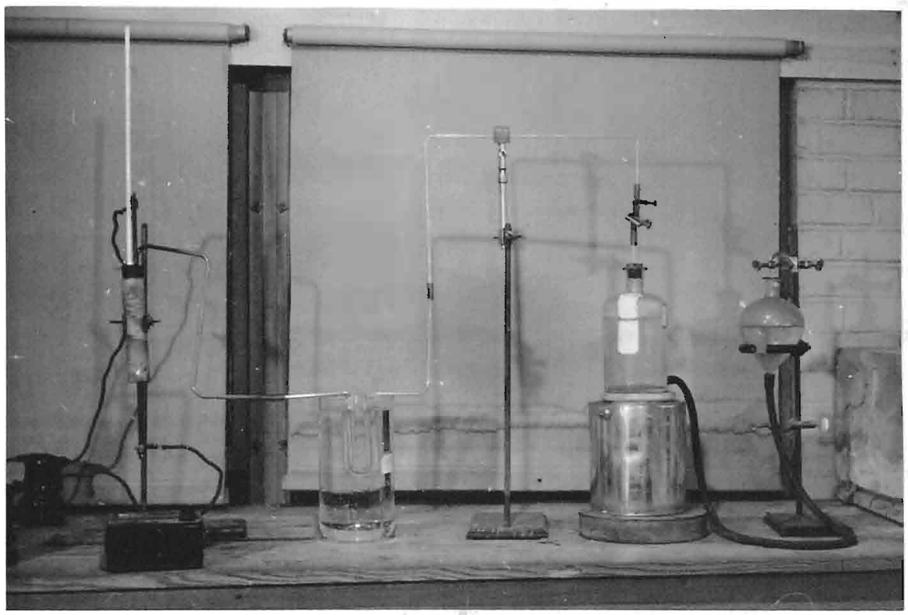
For each determination, the voltage, current, power, and temperatures were read, and the resistance and power factor calculated at time intervals. The size and weight of cores, the salt water saturation, and the recovery of oil and gas were determined for each run. Runs were made at power input of 40, 60, 80, 100, and 120 watts. In the following tables test number 1 was conducted at 40 watts, test number 2 at 60 watts, test number 3 at 80 watts, test number 4 at 100 watts, and test number 5 at 120 watts.

The weight of gas was calculated by using an average molecular weight based on the gas analysis. The weight of oil was determined by the weight increase of the reaction tube for the heating test. This weight increase was considered to be oil and water. The water content was taken as the increase in weight due to the salt water saturation plus the original water content determined by extractions. The oil recovery was calculated as the gain in weight of the apparatus less the weight of water. The oil recovery was expressed in terms of per cent of the oil content determined by extraction.



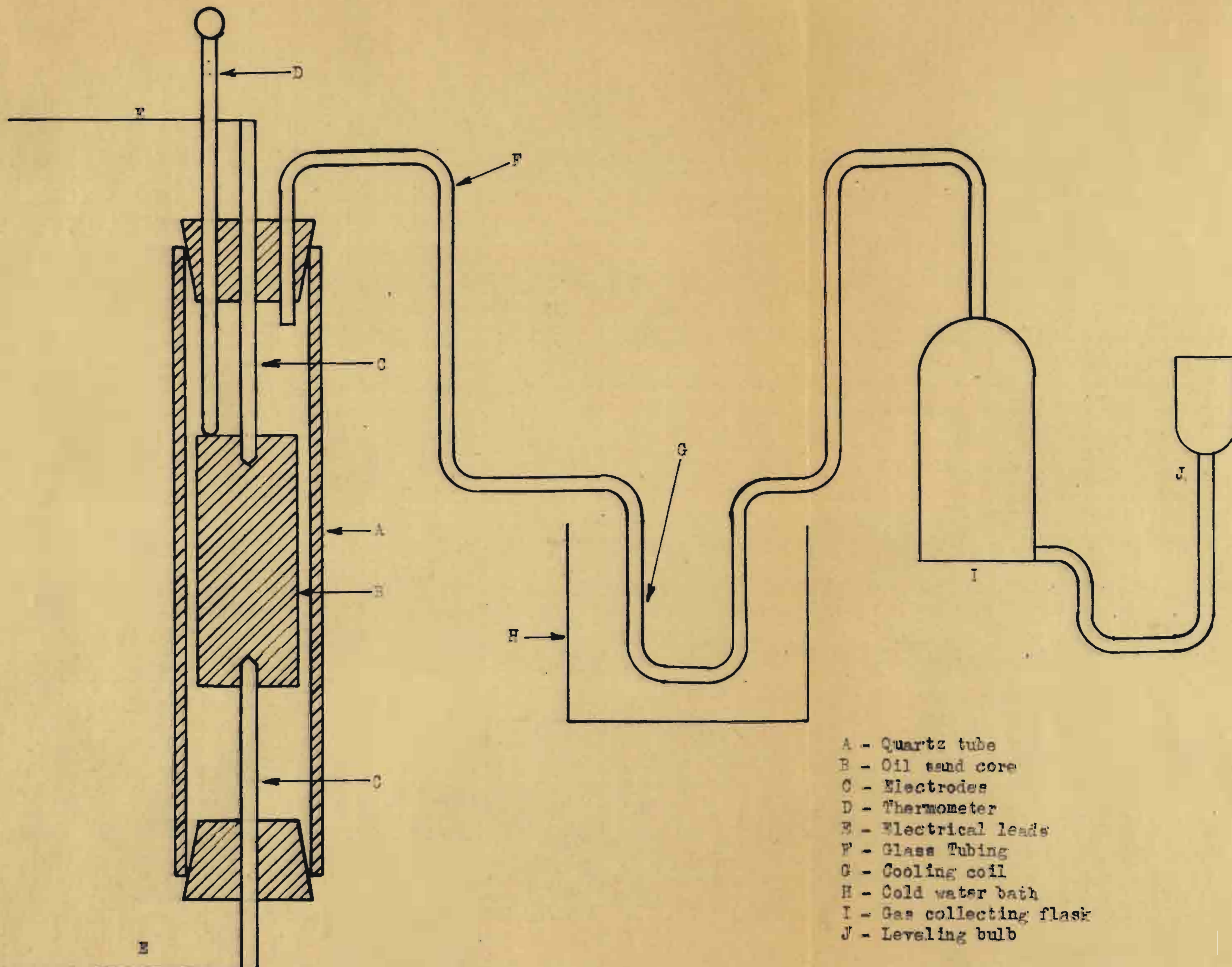
APPARATUS FOR ELECTRICAL HEATING OF OIL SAND CORES

Figure 4



APPARATUS FOR ELECTRICAL HEATING OF OIL SAND CORES

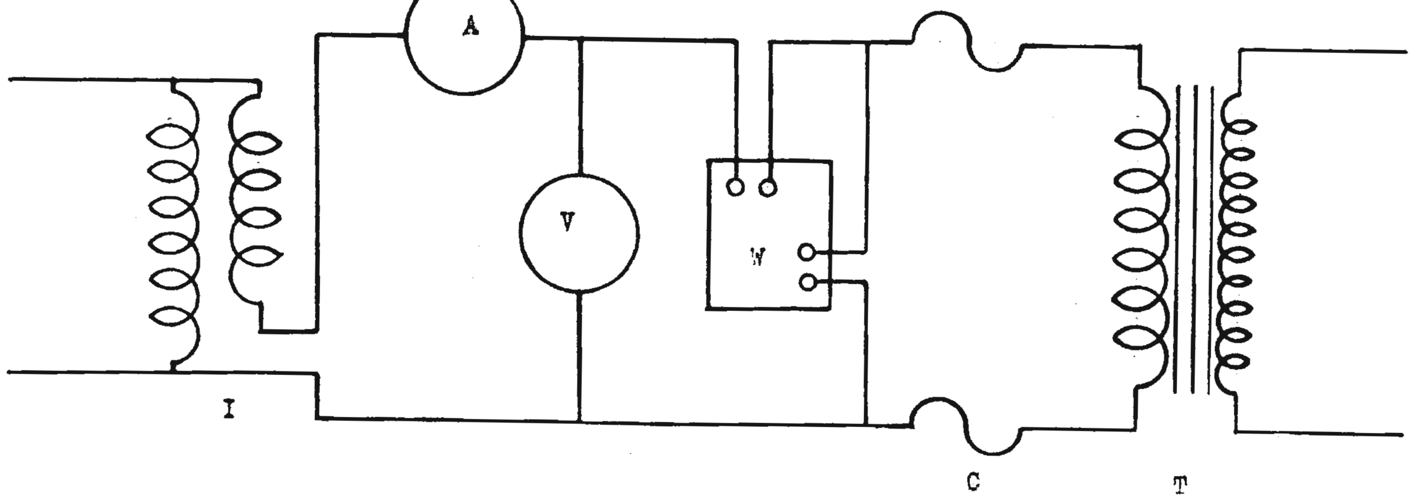
Figure 5



A - Quartz tube
B - Oil sand core
C - Electrodes
D - Thermometer
E - Electrical leads
F - Glass Tubing
G - Cooling coil
H - Cold water bath
I - Gas collecting flask
J - Leveling bulb

Figure 6

DIAGRAM OF APPARATUS



C - Circuit Breaker
A - Ammeter (0-5, 0-10 amperes)
V - Voltmeter (0-300 volts)
W - Wattmeter (0-5, 0-10 amperes, 0-300 volts)
I - Induction Regulator (7.5 kva, 110/220 volts)
T - Transformer (6900, 2300/220, 110 voltage ratio)

Figure 7

DIAGRAM OF ELECTRICAL APPARATUS

ELECTRICAL EQUIPMENT

1. Induction voltage regulator, General Electric Company, Type MK, No. 9616142, 6 KVA, 120, 240 volts, 0-50, 0-25 amps.
2. Voltmeter, Westinghouse Co., 0-300 v., Type KA-25, No. 2392746.
3. Ammeter, Westinghouse Co., 0-5, 0-10 Amps, Type KA-25, No. 2405630.
4. Wattmeter, Westinghouse Co., 120/240 volts, 5/10 amps, Type KY-25, No. 2405631.
5. Overload Circuit Breaker, 25 amps, 480 volts, No. 418132.
6. Transformer, General Electric Co., 7.5 KVA, 1987/2300/6900/11950 to 115/230 volts, Type H, No. 4830823.
7. Milliammeter, Sensitive Research Instrument Corporation, 0-500 Milliamperes, No. 31224.

TABLE 12

CURRENT FLOW BEFORE BREAKDOWN, MISSOURI SANDSTONE

Impressed voltage	Current flow, amperes				
	Test 1	Test 2	Test 3	Test 4	Test 5
600				0.005	
750	0.025	0.005	0.020		
900	0.050		0.025	0.010	0.020
1200	0.075	0.020	0.050		0.030
1500	0	0.030	0	0.005	0.035
1800		0.050			0.040
2100		0.080		0.010	0.035
2400		0		0.015	0.020
2700				0.050	0.020
3000					0.035
3300					0.020
3600					0.015
3900					

TABLE 13

BREAKDOWN POTENTIALS FOR MISSOURI SANDSTONE

Length of core, cm.	Salt water saturation, per cent of pore space	Breakdown potential, volts
4.62	28.67	3900
3.79	30.03	2700
3.70	17.52	3600
4.85	22.53	5100
4.92	32.93	4500
4.79	24.58	6000
4.37	18.83	4500

TABLE 14

VARIATION OF CURRENT AND VOLTAGE AFTER BREAKTHROUGH FOR POWER INPUT OF 40 WATTS

Voltage	Current, amperes	Time, min.	Temperature, °C	Resistance, ohms	Volt-amperes
210	0	0	50		
210	0.15	1		1400	31.5
210	0.15	7	100	1400	31.5
210	0.16	11	130	1310	33.6
210	0.17	17	150	1235	35.7
210	0.175	20	158	1200	36.7
210	0.178	25	168	1180	37.4
210	0.180	30	174	1165	37.8
210	0.183	40	182	1146	38.4
210	0.180	50	185	1165	37.8
210	0.180	60	184	1165	37.8
210	0.185	80	190	1135	38.8
210	0.192	100	196	1092	40.3
210	0.190	120	200	1106	39.9
210	0.20	130	202	1050	42.0
210	0.25	140		840	52.5
210	0.35	145	210	600	73.5
150	0.40	147		375	60.0
100	0.60	150	220	167	60.0
90	0.7	155	250	128.6	63.0

TABLE 14 (Continued)

Voltage	Current, amperes	Time, min.	Temperature, °C	Resistance, ohms	Volt-amperes
90	0.5	160		180	45.0
100	0.7	165	245	143	70.0
100	0.1	166		1000	10.0
110	0.3	168		367	33.0
120	0.1	170		1200	12.0
150	0.1	172		1500	15.0
180	0.1	174		1800	18.0
100	0.5	175	260	200	50.0
100	1.0	180	280	100	100.0

TABLE 15

VARIATION OF CURRENT AND VOLTAGE AFTER BREAKTHROUGH FOR POWER INPUT OF 60 WATTS

Power, watts	Voltage	Current, amperes	Time, min.	Temperature, ^{o}C	Resistance ohms	Volt-amperes	Power factor
60	290	0.2	0	30	1450	58	
60	283	0.2	1		1415	56.6	
60	265	0.2	3		1325	53	
60	236	0.3	5		753	70.8	0.847
60	182	0.4	8		455	72.8	0.825
60	125	0.6	11		208	75.0	0.800
60	115	0.6	13	120	191	69.0	0.870
60	110	0.65	15	130	169	71.5	0.839
60	100	0.68	18		147	68.0	0.833
60	97	0.73	23	154	133	70.8	0.847
60	92	0.77	26	160	119	70.8	0.847
60	90	0.78	30	160	115	70.2	0.855
60	87	0.80	35	170	119	69.6	0.862
60	75	0.95	40	176	89	71.2	0.843
60	86	0.89	45	180	96.6	76.6	0.783
60	85	0.83	54		103	70.5	0.851
60	77	0.89	56		86.5	68.6	0.881
60	76	0.91	57		83.5	69.2	0.867
60	76	0.92	60	184	82.6	69.8	0.859
60	73	0.97	64		75.2	70.8	0.848
60	75	0.92	68		81.5	69.0	0.870
60	75	0.93	70	187	80.7	69.7	0.861

TABLE 16

VARIATION OF CURRENT AND VOLTAGE AFTER BREAKTHROUGH FOR POWER INPUT OF 80 WATTS

Power watts	Voltage	Current, amperes	Time, min.	Temperature, °C	Resistance ohms	Volt-amperes	Power factor
60	300	0.	0		1500	60	
65	300	0.25	1	100	1200	75	0.867
75	300	0.3	2	140	1000	90	0.833
80	250	0.35	2.5		714	87.5	0.914
80	200	0.45	3	180	445	90	0.833
80	180		4	220			
80	155	0.60	5	242	258	93	0.860
80	145	0.65	6	261	223	94.2	0.850
80	124	0.73	8	286	170	90.5	0.884
80	112	0.82	10	302	136.6	91.8	0.872
80	102	0.90	12	312	113.3	91.8	0.872
80	95	0.95	14	321	100	90.3	0.886
80	90	1.0	16	326	90	90.0	0.833
80	85	1.02	18	330	83.3	86.6	0.924
80	83	1.05	20	330	79	87.1	0.919
80	79	1.11	25	328	71.1	87.7	0.912
80	76	1.14	30	333	66.7	86.6	0.924
80	75	1.17	35	338	64.1	87.7	0.912
80	73	1.19	40	338	61.3	86.8	0.922
80	72	1.22	45	338	59.0	87.8	0.912
80	70	1.24	50	336	56.4	86.8	0.922
80	70	1.26	55	336	55.5	88.2	0.911
80	69	1.28	60	336	53.9	88.3	0.906

TABLE 17

VARIATION OF CURRENT AND VOLTAGE AFTER BREAKTHROUGH FOR POWER INPUT OF 100 WATTS

Power, watts	Voltage	Current, amperes	Time, min.	Temperature, °C	Resistance ohms	Volt-amperes	Power factor
	300	0.08	0		3750	24	
100	250	0.4	0.5		625	100	1.0
100	200	0.6	1		333	120	0.833
100	150	0.68	1.5		221	102	0.980
100	125	0.75	2	110	167	93.7	
100	107	1.0	2.5	128	107	107	0.935
100	93	1.10	3	142	84.5	102	0.980
100	85	1.21	3.5	154	70.2	103	0.971
100	80	1.32	4	166	60.5	105.6	0.948
100	72	1.48	5	188	48.7	106.5	0.939
100	67	1.63	6	204	41.2	109.2	0.916
100	62	1.75	7	216	35.4	108.5	0.922
100	59	1.83	8	226	32.3	108.0	0.925
100	54	1.95	10	244	27.7	105.3	0.950
40	55		11				
60	100	0.6	13		167	60.0	1.0
45	120	0.4	14		300	48.0	0.938
20	150	0.2	14.5		750	30.0	
15	170	0.15	15	290	1133	25.5	

TABLE 18

VARIATION OF CURRENT AND VOLTAGE AFTER BREAKTHROUGH FOR POWER INPUT OF 120 WATTS

Power, watts	Voltage	Current, amperes	Temperature °C	Time, min.	Resistance ohms	Volt-amperes	Power factor
50	300	0.2	100	0	3000	60	0.833
60	300	0.2		0.5	3000	60	1.0
60	300	0.21		1	1428	63	0.952
65	300	0.22		2	1364	66	0.986
65	300	0.23	112	3	1364	66	0.986
70	300	0.23		4	1303	69	
80	300	0.24	128	5	1250	72	
100	200	0.40	140	6	750	120	
120	285	0.5		6.5	570	142.5	0.842
120	230	0.58		7	397	133.5	0.900
120	200	0.68	150	7.5	294	132	0.909
120	175	0.78		8	224	136.5	0.879
120	150	0.85		8.5	176	127.4	0.941
120	137	0.92		9	149	126	0.952
120	125	0.97		9.5	129	121.2	0.992
120	121	1.0	180	10	121	121	0.992
120	106	1.15		11	92.2	122	0.984
120	98	1.28	198	12	76.6	125.3	0.957
120	89	1.37	205	13	65.0	121.9	0.986
20	150	0.15		14.5	1000	22.5	0.888
10	200	0.05	210	15	4000	10	1.0
10	250	0.05		15.5	5000	10	1.0

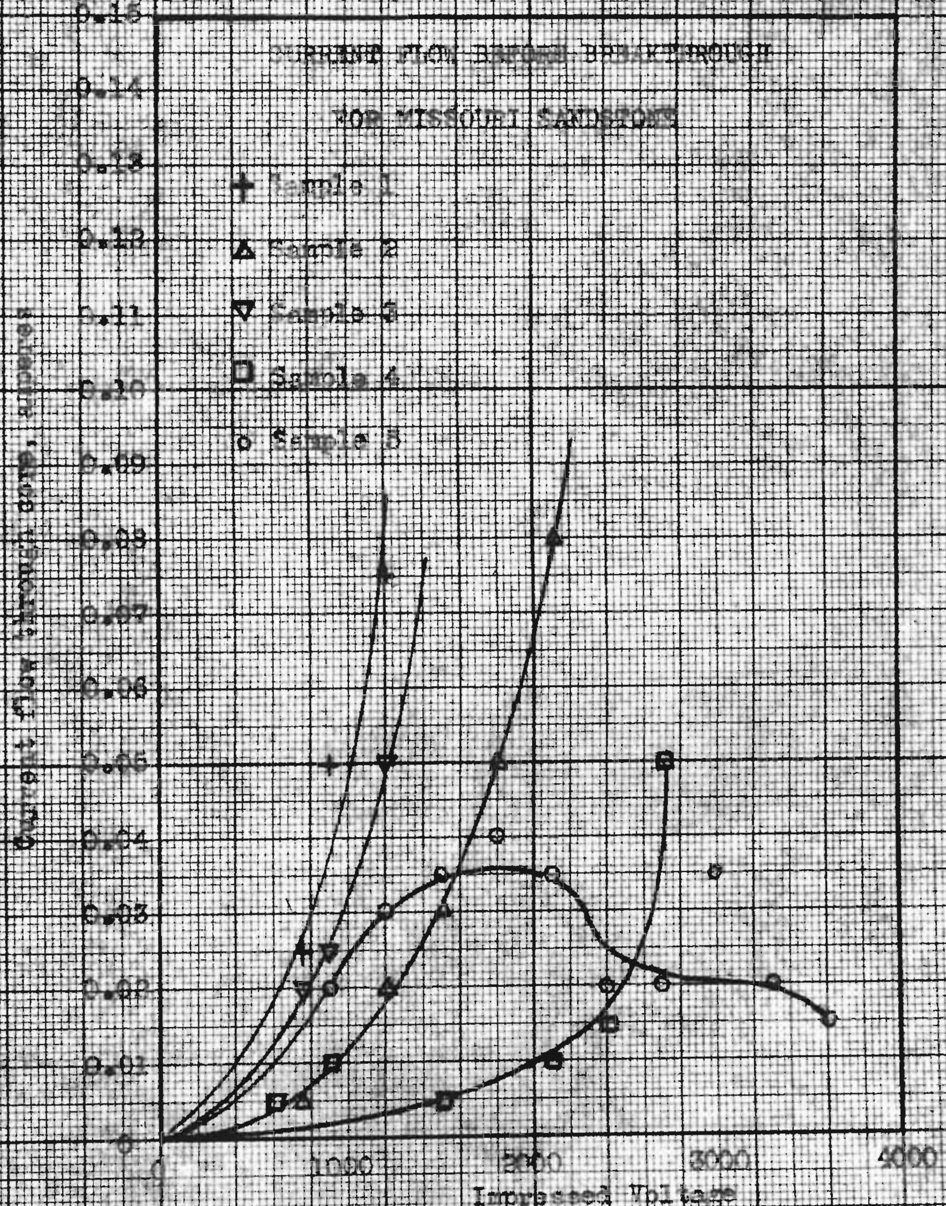

CURRENT FLOW BEFORE BREAKTHROUGH
FOR MISSOURI SANDSTONE
Sample 1
Sample 2
Sample 3
Sample 4
Sample 5
Current flow through core, amperes
0.15
0.14
0.13
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1000
2000
3000
4000
Impressed Voltage

Figure 3

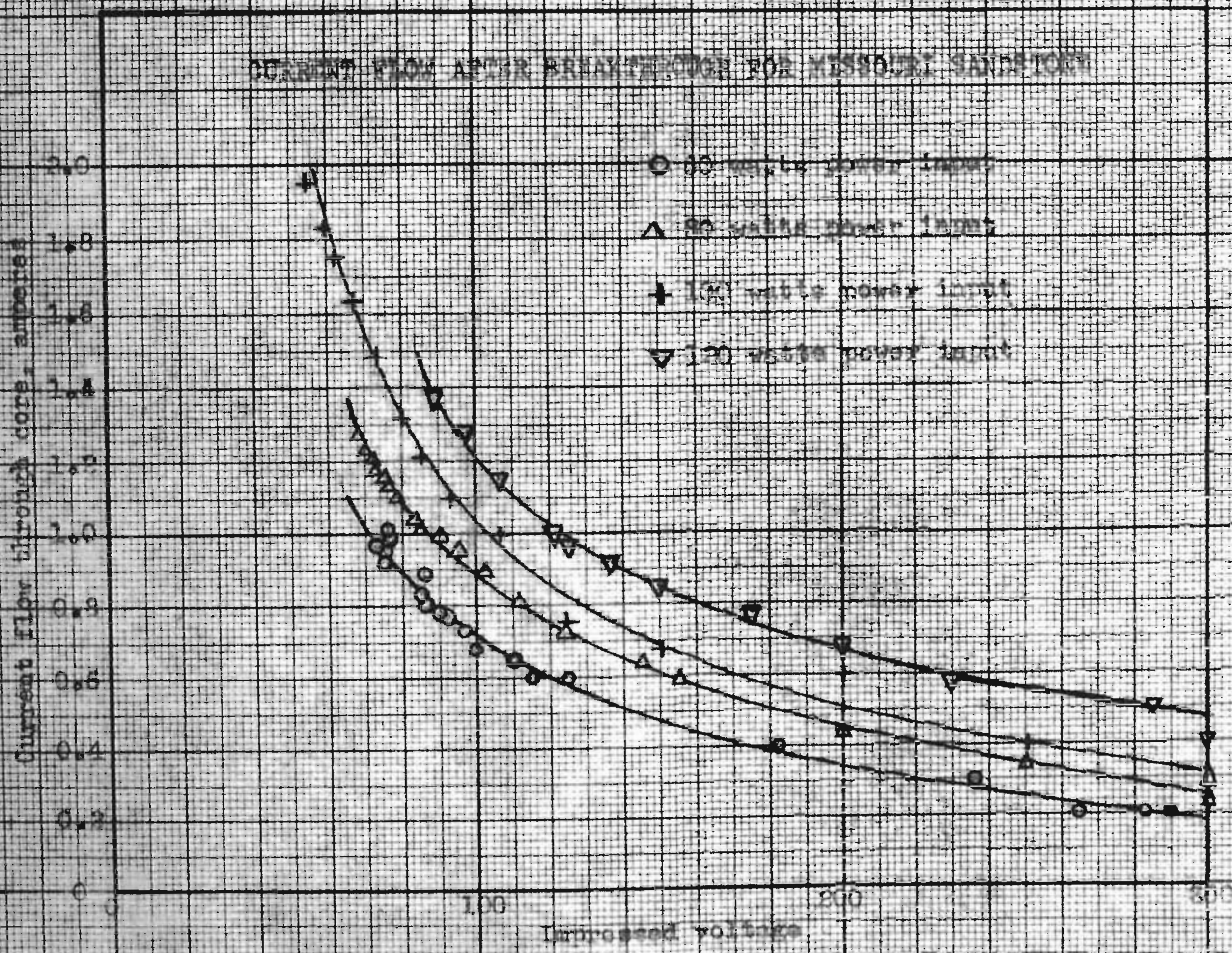

CURRENT FLOW AFTER BREAKTHROUGH FOR MISSOURI SANDSTONE
60 watts power input
80 watts power input
100 watts power input
120 watts power input
Current flow through core, amperes
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
100
200
300
Impressed voltage

Figure 9

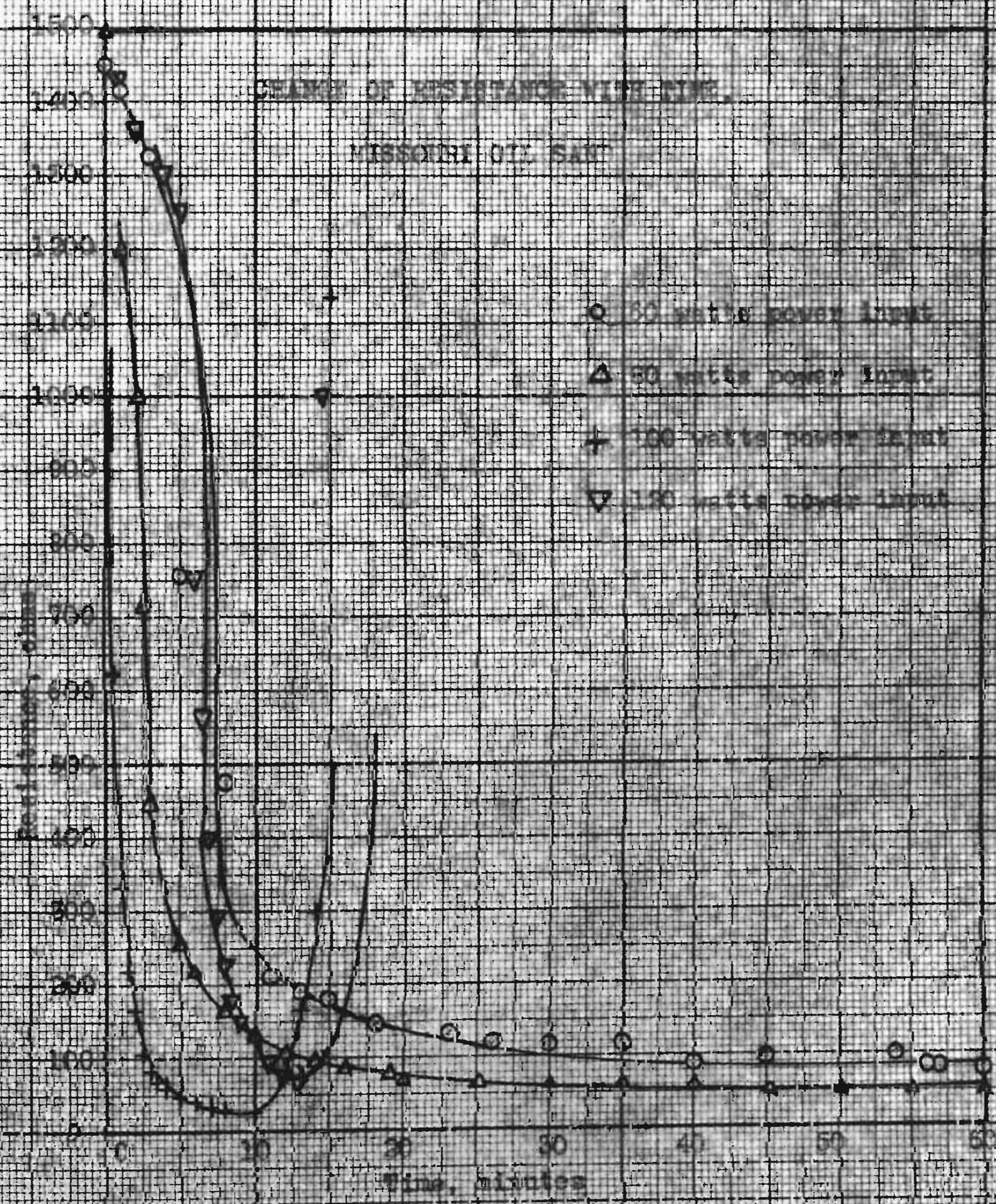

CHANGE OF RESISTANCE WITH TIME.
MISSOURI OIL SAND
watts power input
Time, minutes
0
10
20
30
40
50
60
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0

Figure 10

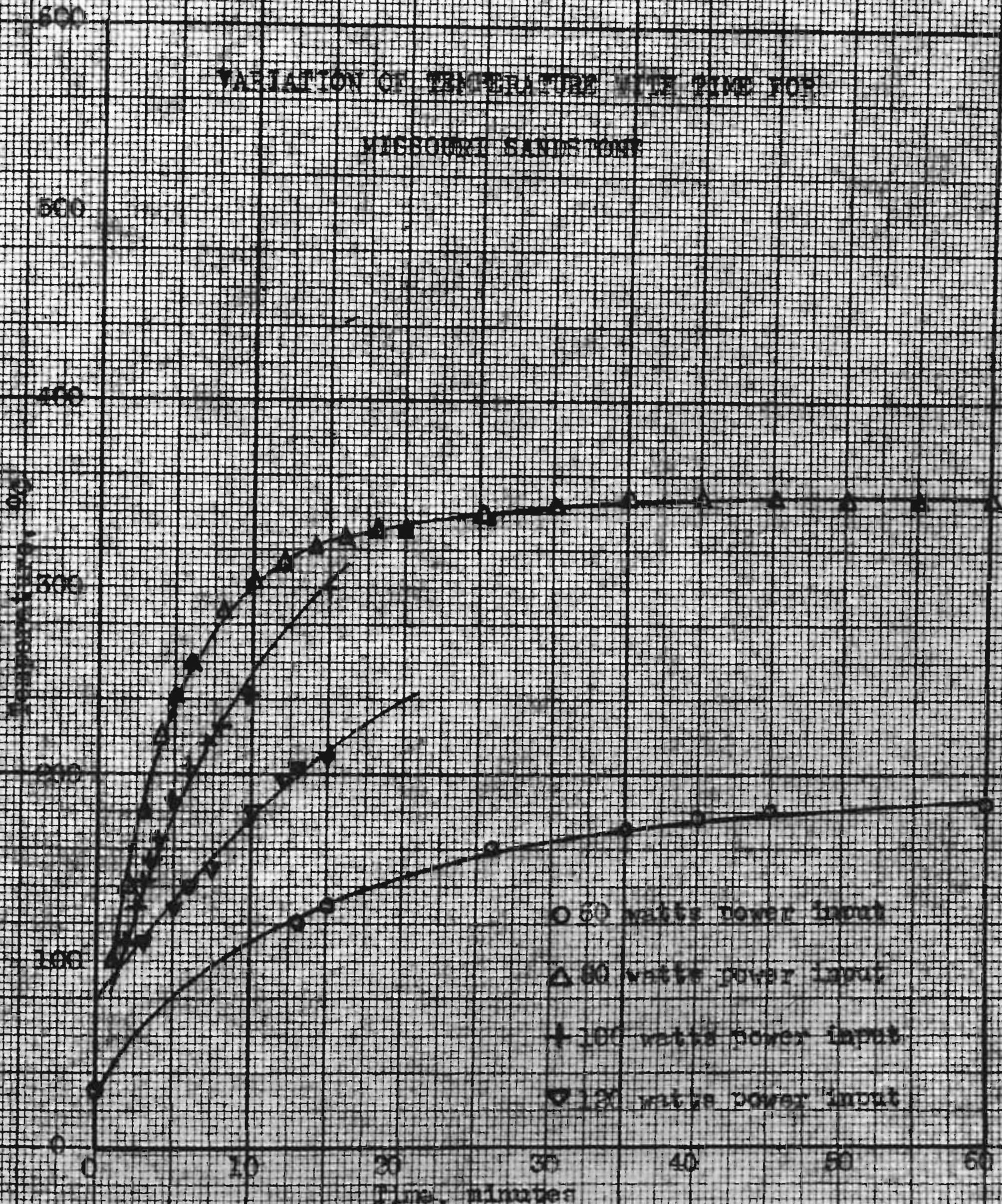

VARIATION OF TEMPERATURE WITH TIME FOR
MISSOURI SANDSTONE
600
500
400
300
200
100
0
0
10
20
30
40
50
60
Time, minutes
50 watts power input
60 watts power input
100 watts power input
120 watts power input

Figure 11

TABLE 19

GAS AND OIL RECOVERY

Test number	Power input watts	Oil recovery % of core	Gas recovery % of core	Total hydrocarbon recovery, % of core
1	40	4.71	0.29	5.00
2	60	4.56	0.52	5.08
3	80	4.24	0.68	4.92
4	100	4.45	0.69	5.14
5	120	4.32	0.51	4.83

TABLE 20

RECOVERY OF GAS

Test No.	Volume of gas cc/100 gm core	Gas analysis, % by volume						
		CO_2	C_2H_4	O_2	CO	CH_4	H_2	N_2
1	403	3.0	7.9	5.4	9.0	14.4	33.2	27.1
2	622	3.6	15.2	4.0	6.8	19.8	22.0	28.6
3	786	2.7	19.7	4.6	4.4	15.4	24.6	28.6
4	810	3.2	17.4	5.0	6.0	20.1	21.3	27.0
5	619	3.5	20.1	4.2	6.7	21.3	22.6	21.6

TABLE 21

PER CENT OF TOTAL OIL RECOVERED

Test No.	Power input watts	Oil recovery % of total oil content	Total Hydrocarbon recovery (oil & gas) % total oil content
1	40	84.1	89.3
2	60	81.5	90.6
3	80	75.8	87.9
4	100	79.5	91.8
5	120	77.2	86.3

RECOVERY OF GAS FROM MISSOURI SANDSTONE

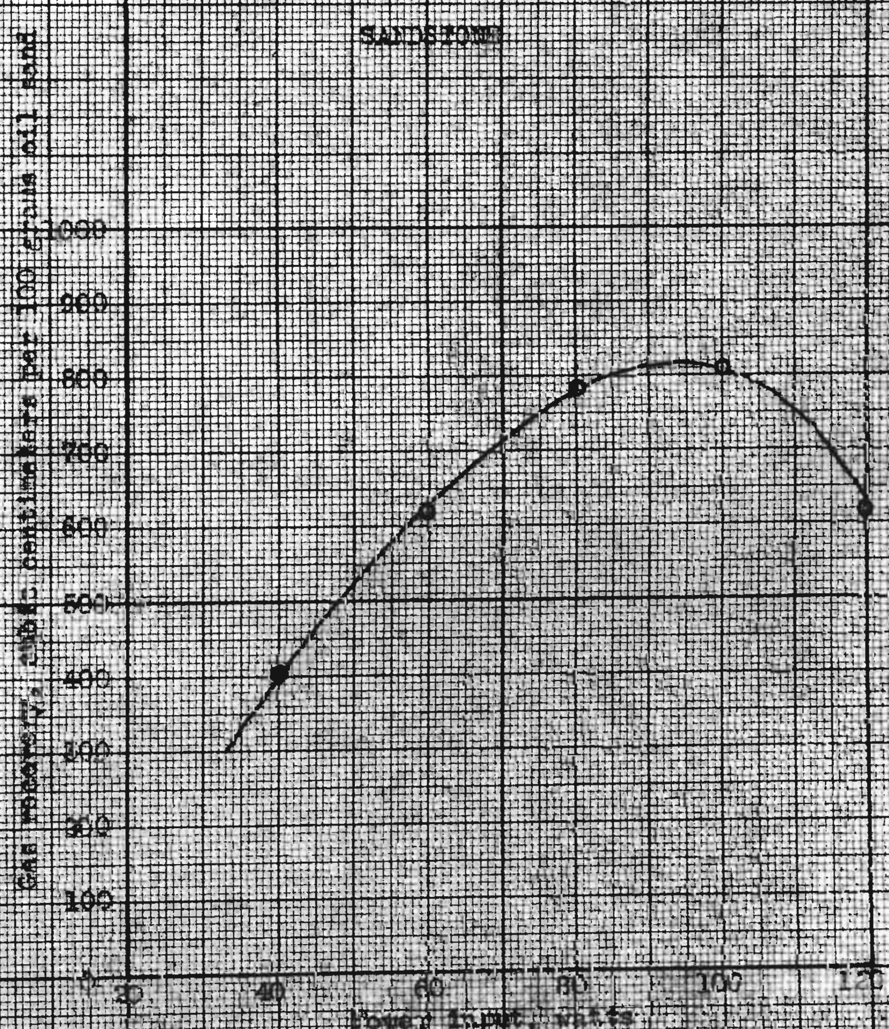


Figure 13

RECOVERY OF OIL AND GAS FROM

MISSOURI SANDSTONE

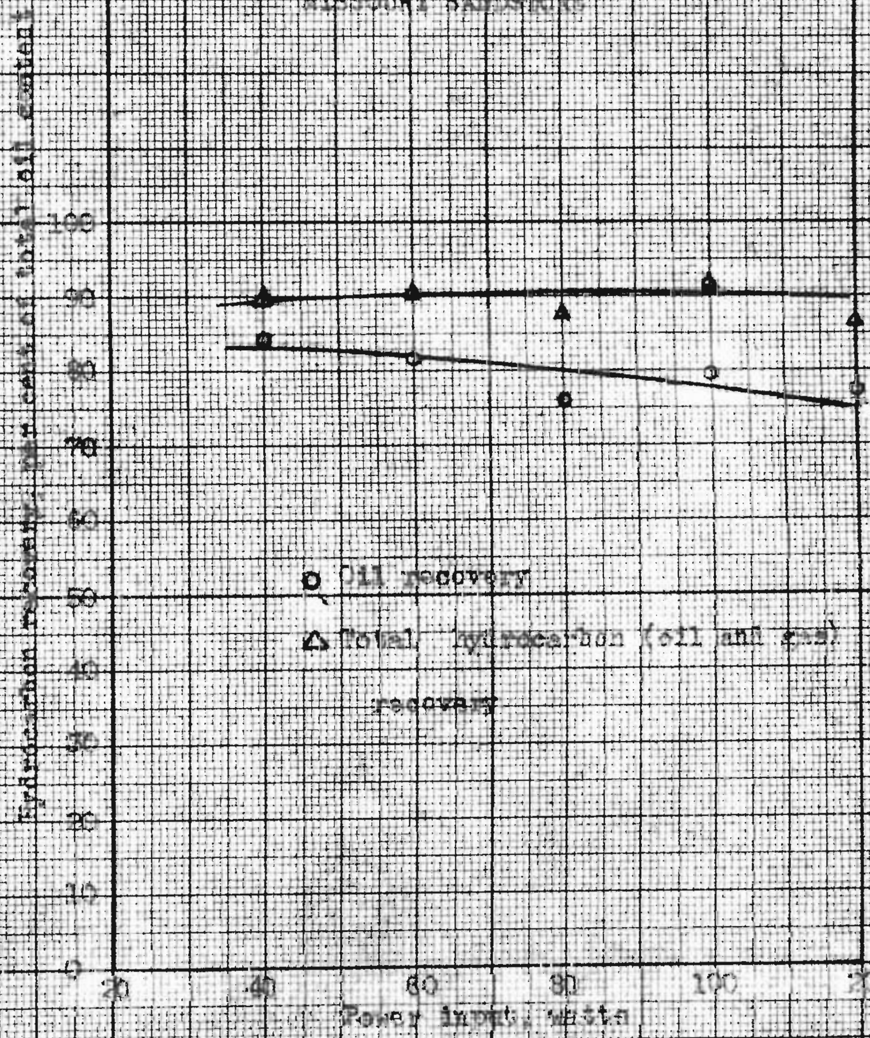


Figure 38

TIME RATE OF CHANGE OF VOLTAGE, CURRENT, RESISTANCE, AND TEMPERATURE FOR POWER INPUT OF 60 WATTS, MISSOURI SANDSTONE

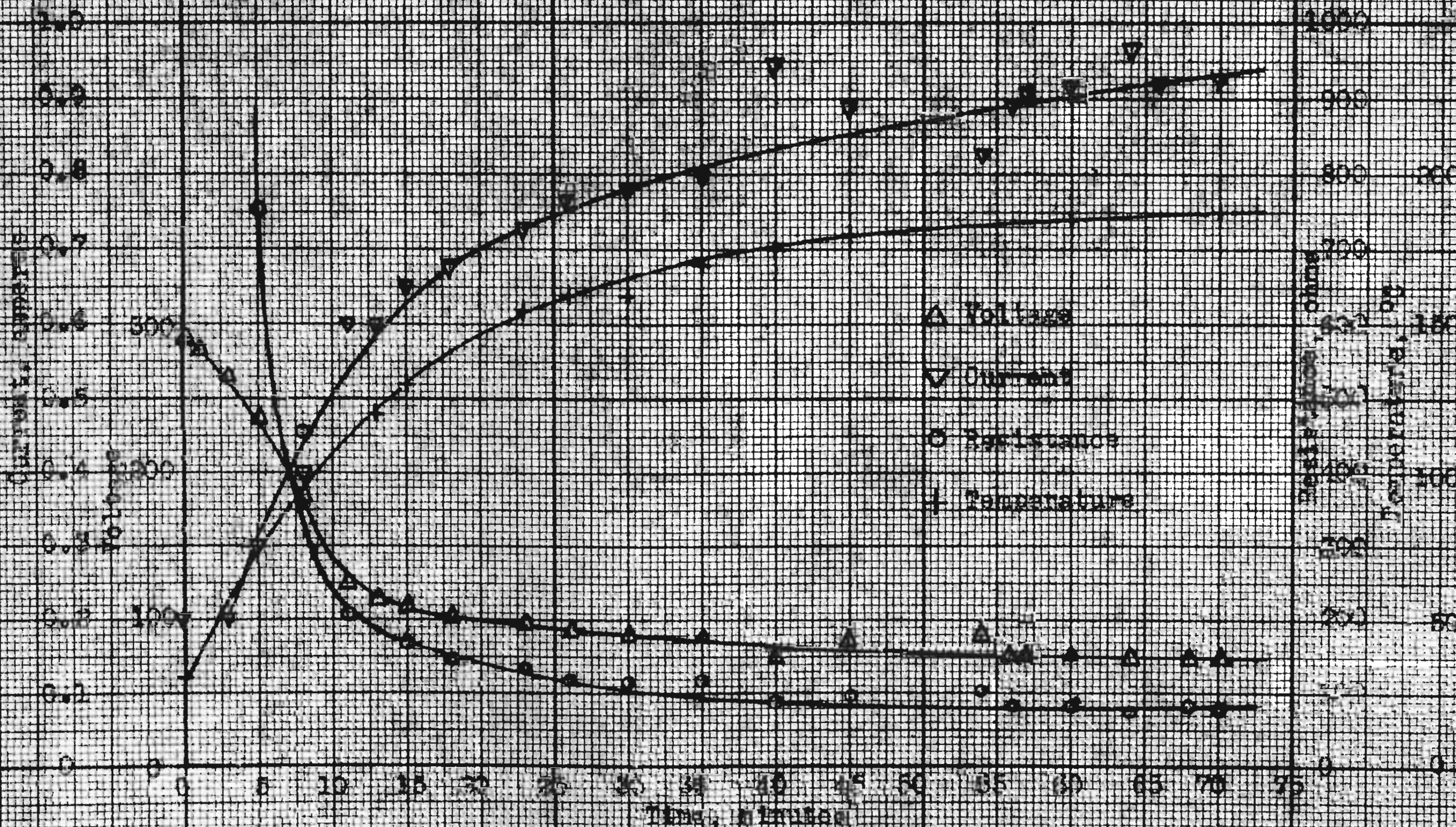


Figure 14

Since the range of voltages and currents is different for the cores before and after breakdown, it was found to be impracticable to plot to current-voltage curve for a complete run on one sheet. The current-voltage curves for the samples before breakdown are shown in figure 9. The current-voltage curve for the cores after breakdown are shown in figure 10. The curves of figure 9 would not correspond to those of figure 10 although they are obtained from the same samples, because the power input was not held constant before breakdown.

The variation of resistance with time for the various samples is shown in figure 11. The resistance is seen to decrease very rapidly with time at first. For the tests at 60 and at 80 watts power input the resistance tends to level off and become substantially constant. For the tests at 100 and 120 watts power input the resistance reaches a minimum then increases.

The power factor varied somewhat for the different runs. For the run at power input of 60 watts the power factor varied from 0.783 to 0.870 and had an average value of 0.842. At power input of 80 watts the power factor varied from 0.833 to 0.924 and had an average value of 0.846. The power factor varied for 0.833 to 1.0 and had an average value of 0.945 at power input of 100 watts. At 120 watts power input the values of the power factor ranged from 0.833 to 1.0 and the average power factor was 0.946.

The variation of temperature with time for the various tests are given in figure 12. These temperatures were surface temperatures measured by placing the thermometer in contact with the surface of the core. It is known that local temperatures in the core reached values greatly in excess of these values because the cores were heated to red heat in certain areas. The greatest temperatures appeared to occur in the vicinity of the electrodes.

Figure 13 shows volume of gas recovered plotted against the power input. Figure 14 shows the recovery of oil and the total hydrocarbon recovery as a function of the power input. It can be seen from the curves that the total hydrocarbon recovery is not greatly affected by the power input. In general, as the power input was increased the gas recovery increased and the oil recovery decreased. The total hydrocarbon recovery was about 90 per cent. This is approximately equal to the recovery obtained by retorting. The recovery obtained by retorting was 91.6 per cent. It is evidently possible to recover most of the oil in the core even at power rates of 40 watts for these small sized cores.

The main effect of power input on the oil recovery seemed to be that increasing the power input caused more of the oil to be converted to gas while the total hydrocarbon recovery was not greatly affected.

Since no measurable amount of gas was obtained by retorting, it is probable that most of the gas obtained in the electrical heating tests was formed by thermal cracking of the oil in the core. The carbonization along the path of the current flow would cause the formation of gas. The collected gas contained relatively high percentages of hydrogen and illuminants which might indicate that the gas was formed from cracking of the oil.

In figure 15 the variation of voltage, current, temperature, and resistance are shown as a function of time for one test. This is for the test conducted at a constant power input of 60 watts.

The cores were examined after the tests to see what pattern of current flow would be indicated by the carbonization path. The graphitization was found to be largely on the surface of the core. The penetration of the graphite into the core was slight although there seemed to be some carbonaceous matter within the core in the immediate area of the grahpitized path. The cores contained numerous small fractures especially in the vicinity of the electrodes and along the path of graphitization.

CONCLUSIONS

The results of this investigation indicate that, for the size of cores and ranges of power used in the electrical heating tests, the total hydrocarbon recovery was not greatly affected by the power input. The recovery of gas increased as the power input was increased, and the recovery of oil decreased as the power input was increased. The recovery of hydrocarbons by electrical heatingwas found to be nearly equal to that obtained by retort analysis. The hydrocarbon recovery was about 90% of that originally in the core if expressed in terms of the extraction analysis.

The conductivity of the sand formation was found to increase rapidly with heating after breakthrough. The conductivity of the sand cores were sufficiently high that they could be heated with moderate voltages after breakthrough, although high voltages were required to achieve the initial breakthrough.

The breakthrough caused carbonization of the core which gave the core its conductivity. The increase of conductivity of the core with time indicated that the amount of carbon formed increased as heating progressed, and that when most of the recoverable oil had been driven from the core the carbonization ceased, or materially lessened.

The greater portion of the graphitization and, consequently, the greater portion of the current flow occurred on or near the surface of the sand cores.

High local temperatures were obtained in the vicinity of the electrodes. These temperatures were much higher than the surface temperatures which were determined with the thermometer.

SUMMARY

The recovery of oil and gas from the oil sand cores by electrical heating was investigated and the results compared with the recovery obtained by retorting and by extraction.

The effect of electrical heating on the conductivity of the core was investigated. Data were taken for the variation of voltage and current for the heating of oil sand cores at constant power input.

The effect of power input on the recovery of oil and gas from the cores was investigated.

The graphitization of the cores caused by the passage of current was noted.

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VITA

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